Intrinsic phase-decoherence of electrons by two-level systems

Vipin Srivastava* and Raishma Krishnan†
School of Physics, University of Hyderabad, Hyderabad 500046, India.

The fundamental problem of phase saturation of electrons in a disordered mesoscopic system at very low temperatures is addressed. The disorder in the medium has both static and dynamic components, the latter being in the form of two-level systems (TLSs), which becomes just about the only source of inelastic scattering in the limit $T \rightarrow 0$. We propose that besides the inelastic nature of scattering from the TLSs, the phase-shift of the electrons is also affected by the nature of tunneling in the TLSs. The tunneling becomes incoherent as T decreases due to increasing long-range interactions among TLSs and affects the phase coherence of electrons scattering from them. The competition between this effect, which increases as $\sim T^{-1}$, and that of the scattering rate τ_{e-TLS}^{-1} behaving as $\sim T$ apparently governs the phase-shift of electrons.

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∗ e mail: vpssp@uohyd.ernet.in

† e mail: vpssprs@uohyd.ernet.in

1. **Introduction**

One of the fundamental properties of an electron under quantum mechanical conditions is that the phase of its wavefunction remains coherent over a length of time and space. The electron loses the phase coherence if it interacts with its environment. The coherence-decoherence transition defines the transition from quantum mechanical behaviour of a 'closed' system to the classical behaviour of the same system when it is treated as 'open'. What should comprise 'a system of interest' and its 'environment' with which it may be coupled, depends on how we want to define the problem; the experiments are designed accordingly. For example in the problem of movement of an electron in a random potential, the electron and the impurities or the disordered potential comprise the system of interest while other electrons, phonons and two-level systems (TLSs) etc. form parts of the environment.

For the problem of an electron in a random potential it is now established that the elastic scatterings of the electron under study from the impurities do not dephase it, or randomize its phase [1]. On each such scattering episode the momentum of the electron changes and also the phase of the single-electron wavefunction, but in a deterministic manner. That is the changes are correlated and computable, in principle. Normally the phase relaxation length, or the length over which the phase has reversed, can be much larger than the elastic mean free path. The inelastic scattering events due to electron-phonon (e-ph), electron-electron (e-e) or e-TLS interactions, on the other hand randomize the phase of the electron wavefunction. It was believed until recently that in the limit of temperature $T \rightarrow 0$ the inelastic events could be minimized and consequently the phase-decoherence time τ_ϕ and the phase-coherence length L_ϕ could be arbitrarily large.

Under normal conditions achievable in experiments a disordered system can be viewed as a jigsaw of phase-coherent units, where each unit is of mesoscopic length scale and contains many elastic scatterers. To study the long-range phase-coherence one ought to do experiments on a sample of mesoscopic size and weak localization is an appropriate phenomenon to investigate for analyzing different scattering processes for it is sensitive to phase relaxation and also momentum relaxation. All electrons incident in the same state acquire the same phase shift after going through a given set of elastic scatterers so much so that a time reversed course of the same collisions can restore the original phase of the wavefunction. An inelastic collision in the course destroys the phase memory of the electron irrevocably.

2. **Saturation of phase-decoherence time**

Some recent experiments [2,3] along these lines have shown that τ_ϕ, and in turn L_ϕ, approaches a *finite* temperature independent value below a temperature that may lie between a few mK and 10K depending on the system under study. It has been observed in a wide variety of disordered conductors that τ_ϕ saturates to a value between 10^{-9}

sec and 10^{-12} sec below $4K$ depending on the system. It is further claimed that this phase decoherence is intrinsic in character, that is, it should not depend on the coupling with extrinsic environmental factors. This led to the suggestion that the decoherence could be caused by the zero point oscillations of the electrons [3]. This point of view was, however, refuted on the simple ground that the energy of the zero point oscillations cannot be transferred in the course of inelastic collisions of the electron in question with the electrons around it.

Not withstanding the mechanism of dephasing, which is a matter of intense debate, the result is undoubtedly of fundamental importance and of far reaching consequences. A number of phenomena, including electron localization, that depend on quantum interference would require rethinking. As for localization, the experimental result [3] poses a serious puzzle by indicating that the zero temperature dephasing length $L_\phi(T=0)$ is much smaller than the typical localization length ξ. This would have the serious implication that large localized states (or weak localization, WL) may not exist. There ought to be a competition between quenched or static disorder and the factors that limit the intrinsic decoherence time τ_ϕ in deciding the extent of localization even for $T \to 0$. Consequently there could be a lower critical value of disorder below which localization may not happen. (If $L_\phi \sim \frac{\xi}{(k_F l)}$, localization will occur only if $\xi < L_\phi$, i.e. $k_F l < 1$, i.e. the WL regime for which $k_F l \sim 1$, as it is understood now, should actually be non-existent; k_F is the Fermi wave vector and l is the elastic mean free path.)

3. **Sources of dephasing**

Phonons are the most obvious source of dephasing, but they have to be ruled out in the temperature range in which τ_ϕ has been observed to saturate. The inelastic processes that may persist at such low temperatures are e-e and e-TLS interactions.

While e-e interaction is generally considered to be a good candidate as a phase randomizing agent at low temperatures it should be noted that the samples in the experiments in question have fairly low concentration of electrons, $\sim 10^{12} cm^{-2}$ [4]. The e-e interaction energy should be considerably low in these samples as compared to that in earlier experiments when the electron density used to be much higher. It is therefore not clear as to what extent will these interactions be instrumental in the dephasing phenomenon. These could at most be quasi-elastic which would imply that there would have to be many collisions of this kind before the electron's phase would change by 2π.

We will investigate in some detail the interaction of electrons with TLSs as a plausible mechanism of the phase decoherence. In this scenario one studies the movement of an electron under the combined influence of static or quenched disorder and a dynamical environment due to an atom or a group of atoms moving back and forth between two locations in space which correspond to minimum energy states seperated by a potential barrier in the configuration space. While the movement of an electron under the influence of a static disorder is diffusive, the dynamical disturbances in space caused by TLSs can

make the electron move into another state inelastically even at $T = 0$. We expect that the inelastic scattering from TLSs should dominate at very low temperatures when other sources of inelastic scattering have diminished or become ineffective. Inelastic scattering from TLSs as the source of decoherence of an electron has been discussed in the literature [5-7], but we have a very different mechanism to propose for the dephasing phenomenon.

Ovadyahu [5] first found in some of his indium oxide samples with low resistivity ($k_F l > 2$) that inelastic scattering time was much shorter than the e-e interaction time. The results fitted well when e-TLS scattering was invoked as the phase-breaking mechanism. Zawadowski et al. [6] considered non-magnetic TLSs having degenerate Kondo ground states. In a certain temperature range the TLSs exhibit non-Fermi liquid (NFL) behaviour which apparently is the signature of dephasing. They propose that the scattering of an electron from a TLS of this type changes the state of the TLS and thus the environment of the electron changes. This acts back on the electron and causes the dephasing. Imry et al. [7] proposed a perturbative theory in electron-environment interaction where τ_ϕ is much longer than the quasi-elastic scattering time τ. The scattered electron undergoes a phase-shift due to the motion of the scatterer. The phase-shift changes the conductance and also causes dephasing. If the defect motion is slower than the time scale of electronic motion only the conductance changes, but if the defect moves faster than the electronic motion then dephasing also happens.

4. **Our proposal**

Our arguments are a bit along the lines of Imry et al. [7] but only to start with. We propose a novel mechanism for the saturation of τ_ϕ which accounts for the T-independence of τ_ϕ. First of all we propose that the phase-shift of an inelastically scattering electron should depend not only on the fact that the scattering it is undergoing is inelastic in nature but also on the character of the scatterer. The latter should be particularly significant in the case of dynamical scatterers like TLSs, whose character depends on the nature of the tunneling – whether it is coherent or incoherent.

We can formally write,

$$\tau_\phi = f(\tau_{in}, c), \tag{1}$$

where c is a parameter signifying the character of the inelastic scatterer. In the case of e-TLS scattering $\tau_{in}(= \tau_{e-TLS})$ would predominently depend on temperature and concentration of TLSs. While its dependence on concentration of TLSs is obvious, we understand the dependence of τ_{e-TLS} on T like this: first of all note that the tunneling will have to be assisted by phonons if λ is larger than a certain λ_{min} [8,9] where $e^{-\lambda}$ represents overlap between wavefunctions in the two potential wells of the TLS. Since λ depends inversely on T, the tunneling will be increasingly more difficult as $T \to 0$ and at some point it will become impossible. Below this value of T the system will freeze into one of the configurations represented by the two wells. Thus as T decreases the tunneling rate of this type of TLSs decreases and consequently the scattering rate, τ^{-1}_{e-TLS} decreases. In simple

terms the rate of tunneling becomes slower than the time scale of the electron movement. However, if the TLS is such that $\lambda < \lambda_{min}$, then tunneling continues to happen even if $T \rightarrow 0$. Such TLSs are particularly significant for the saturation of τ_{ϕ}.

We will now discuss the parameter c in the eqn. (1). The character of a TLS can depend considerably on its interaction with other TLSs. Note that the motion of the tunneling entity (an atom or bunch of them) produces a strain field. If the TLSs are far away from each other or the temperature is not low enough to preclude phonons, then the strain field may not affect other TLSs because it may get weakened or dissipated by phonons. But if the concentration of TLS is high or there are intermediary impurities, then the strain field produced by one TLS can affect the nature of oscillation of other TLSs if the temperature is so low that the dissipation of the strain field by phonons can be ruled out. While an isolated TLS generally oscillates between two wells coherently, the interaction between TLSs can make the oscillations incoherent. This crossover, which happens primarily as a function of decreasing temperature will have its influence on the phase-shift of the electron scattering off the TLS; it should add to the change of phase of the electron, which is otherwise happening due to its scattering from the TLSs.

If the mean interaction between the TLS is represented by an energy J then one can combine with it the local parameter Δ_0 ($\sim e^{-\lambda}$, representing the seperation between the wells of a TLS on the configuration-axis) and describe the TLS-TLS interaction by a dimensionless parameter [10]

$$\mu = J/\Delta_0. \tag{2}$$

If J dominates over the local coupling energy Δ_0 (i.e interaction between TLSs is as large as, or larger than, the coupling between wavefunctions in the two wells of a TLS) then μ will exceed 1 and the local tunneling motion will become incoherent. In glassy systems Δ_0 will have a wide distribution which can be $\propto k_B T$ [11]. Consequently μ can be treated as $\propto T^{-1}$. Note that τ_{e-TLS} is also $\propto T^{-1}$ [12]. In the background of all the above discussion, the implications of both μ and τ_{e-TLS} being $\propto T^{-1}$ are important in so far as the phase change of the electron is concerned.

Let us consider the two situations, $\lambda > \lambda_{min}$ and $\lambda < \lambda_{min}$, separately. Infact both the situations are important at the same time because TLSs satisfying either conditions would be present in the system. In the TLSs for which $\lambda > \lambda_{min}$ since the tunneling must be assisted by phonons, it will increasingly slow down with decreasing temperature. As a result τ_{e-TLS} will increase at a rate $\propto T^{-1}$. But, while the tunneling rate slows down the *nature* of tunneling changes from coherent to incoherent at the same rate, namely T^{-1} due to increasing TLS-TLS interaction. If according to Stern et al. [13] e-TLS scattering is turning from inelastic to quasi-elastic and then to elastic with decreasing T and is therefore able to change only the conductance, the phase-shift in the scattered electron will be mainly brought about by the latter factor discussed above, namely the coherent-to-incoherent crossover in the nature of TLSs.

The TLSs with $\lambda < \lambda_{min}$, in which the tunneling occurs in spite of the absence of phonons, change the phase of the electron scattering off them even as $T \rightarrow 0$. This is true

independent of whether the energy exchanged in the scattering process is sufficient for it to be fully inelastic. The phase of the scattered electron in any case changes because the tunneling in these TLSs also becomes incoherent with decreasing T due to long-ranged interactions among TLS.

The incoherence of the tunneling in both types of TLSs increases with decreasing T and accordingly the amount of the phase change of the scattered electron increases. At sufficiently low T when the phase change is about 2π the decoherence time τ_ϕ will saturate and become temperature independent.

5. **Conclusions and comments**

We have argued that the phase decoherence time τ_ϕ of electrons in a disordered mesoscopic system saturates and becomes T-independent at very low temperature due to the following two complementing effects: on one hand with decreasing T the e-TLS scattering weakens and becomes less effective as an inelastic process, but on the other hand this is compensated by the fact that with decreasing T the tunneling in TLSs becomes incoherent due to increasing long-ranged interactions among TLSs and this decoheres the electrons; both these effects balance each other at the same rate, namely T^{-1}, which makes the saturated τ_ϕ independent of T. A good amount of further experimentation is required to ascertain a number of finer points.

First of all it must be checked whether the systems that exhibit τ_ϕ-saturation always have TLSs present in them. This is necessary in order to establish that the suggested mechanism is really a universal one. Experiments are required to identify the types of TLSs, atleast the two types discussed above. Having done this it is necessary to study in greater detail the coherent-incoherent tunneling crossover as a function of T and whether both the above types of TLSs are affected equally as T decreases. Experiments are also needed to ascertain if the e-e interactions in *dilute* electron systems indeed involve sufficient energy to be classified as inelastic at low temperatures.

Finally it could well be, as suggested by Imry et al. [7], that there may be just a temperature range over which τ_ϕ remains saturated, and that at a $T << \hbar/\tau_0$ (τ_0 being the saturation value of τ_ϕ) the τ_ϕ may diverge. Only very careful experimentation can resolve these issues.

We may mention in passing that the rapid development of quantum information processing [14] led to renewed interest in the study of dephasing effects. The studies proposed above would be very vital in this modern context for one of the major obstacles in the way of implementation of quantum computers is the relatively short dephasing time in the solid state devices.

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9. $\lambda_{min} \equiv ln(2\hbar\omega_0/\Delta E)$ where $\hbar\omega_0$ is of the order of zero-point energy and ΔE is the difference between the minima of the two wells of the TLS, i.e. between the diagonal elements of the Hamiltonian for the TLS. The condition $\lambda > \lambda_{min}$ simply means that $\hbar\omega_0 e^{-\lambda}$, the off-diagonal element of the Hamiltonian, is $< \Delta E/2$. That is, ΔE is too large to allow any meaningful correction to the eigen values of the Hamiltonian by the off diagonal elements.

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